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EFFECTS OF ATOMIC EXPLOSIONS ON THE IONOSPHERE

Fred B. Daniels, et al

Signal Corps Engineering Laboratories
Fort Monmouth, New Jersey

January 1953

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1 OF 2

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OPERATION SNAPPER

Project 9.4

EFFECTS OF ATOMIC EXPLOSIONS ON THE IONOSPHERE

REPORT TO THE TEST DIRECTOR

by
Fred B. Daniels
Arthur K. Harris

January 1953

Signal Corps Engineering Laboratories
Fort Monmouth, N.J.

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ABSTRACT

Vertical and oblique incidence radio pulse soundin and oblique incidence C-W transmissions were made during Operation TUMBLER-SNAPPER for the purpose of investigating the effect of an atomic explosion upon the ionosphere and upon radio propagation. The observed effects were attributed to the local changes of ion density caused by the blast wave passing through the existing ionized layers. Disturbance to radio propagation was found to exist for only a few minutes, and would have been troublesome to voice communication only. It was found that the observed phenomena may serve as a means of long-range detection of atomic explosions under certain conditions. The value of large explosions as a tool in ionospheric research was also established.

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Mr. Alan S. Gross who wrote the section on instrumentation and reviewed the report and Mr. David T. Goldman who assisted in the analysis of data.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The objective of Project 9.4 was to obtain data on the effects of an atomic explosion upon the ionosphere and the consequent effects upon ionospheric radio propagation. A further objective was to investigate the possibilities of large explosions as a tool in ionospheric research.

1.2 BACKGROUND AND THEORETICAL DATA

1.2.1 GREENHOUSE Tests

During the GREENHOUSE tests, 8.3B program personnel operated a C-3 vertical incidence ionospheric recorder approximately 15 miles from the blast site. The C-3 Automatic Ionosphere Recorder is a device which measures and records the virtual height and critical frequencies of the ionized regions of the upper atmosphere. To accomplish this, pulses of radio frequency are transmitted over a range of frequencies from 1 to 25 megacycles. The transmitted pulses are reflected from the various layers of the ionosphere, picked up by the receiver of the C-3 equipment and displayed as oscilloscope traces which show the virtual height of the reflections versus transmitted frequency. A more detailed discussion of the method and of the interpretation of the results may be found in Circular Number 462 of the National Bureau of Standards 5/.

The authors of the present report have examined C-3 records obtained during the GREENHOUSE tests and have found that one of the most significant effects observed was a rising sequence of reflections of the transmitted radio pulses as the blast wave passed through the E layer; this effect was quite pronounced in the George shot. The first of these reflections was observed at plus 7.5 minutes at a height of about 110 km; (this sequence of reflections rose with the approximate velocity of sound for about 2½ minutes and disappeared after reaching a height of about 155 km). In addition to this effect, the normal E, F1 and F2 reflections gradually weakened, starting at plus 4 minutes, until they had almost vanished (plus 8 minutes). At plus 8.5 minutes, the F2-layer reflection reappeared for a brief interval and then disappeared again, following which a two-hop F2 reflection appeared, unaccompanied by a single-hop reflection. At plus 15 minutes, all reflections reappeared, but did not reach full strength until about 2½ hours after the blast. A partial fadeout of such duration was not observed during

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any of the other tests and there is still some doubt as to its cause. However, it may have been caused by absorption of the radio waves by the atomic cloud, as the cloud was not dispersed by the wind as rapidly as had been anticipated from meteorological forecasts. The fact that the absorption was most pronounced at the lower frequencies supports this hypothesis.

1.2.2 BUSTER Shots

During the BUSTER shots, Project 6.9 personnel operated a short range ionospheric radio circuit. The transmitter and receiver sites were separated by about 30 miles and were so located that the radio wave was reflected directly above the blast site; the operating frequencies were so chosen that only F-layer propagation would occur. Data obtained during the Charlie, Dog and Easy shots indicated the presence of a disturbance to the radio signal which commenced at about plus 6 minutes and lasted for a period of the order of 15 minutes. A C-3 ionospheric recorder was also operated during these tests and there was some indication that E-layer reflections were obtained which were similar to those observed on the GREENHOUSE George test (i.e., rising with the velocity of sound). However, rapidly changing stratification of the sporadic-E layer is a common phenomenon at any time, and the effect noticed may have had no connection with the blast. (The effect observed during GREENHOUSE was much more pronounced and unaccompanied by other E-layer stratification.) During the BUSTER shots, the C-3 records of Dog and Easy shots exhibited "spread echoes" near the cusp corresponding to E-layer penetration. These records also had additional cusps in the F-layer trace which moved to the right (increasing frequency) from about plus 7 to plus 10 minutes.

1.2.3 Theory

All of the effects described above can be ascribed with high probability to scattering or reflection of the radio waves by the fluctuations of ion density caused by the blast wave as it passes through the ionized layers, which begin at about 100 km above the earth's surface. It has been demonstrated by Rawer[8] (see Bibliography for references) that a layer of electrons will reflect radio waves, the maximum frequency of reflection depending upon the electron density and the angle of incidence. The percentage of energy reflected will depend upon the thickness of the layer, as well as upon the other parameters. (It is this type of reflection which is responsible for normal ionospheric radio propagation.) Furthermore, a layer of increased electron density occurring in an already existing layer of electrons will reflect radio waves of a higher frequency than that which would normally be reflected from the layer. A sound wave consists of alternations in the molecular density of the medium; if these alternations are accompanied by proportionate changes in the density of the free electrons, a sound wave passing through the ionosphere would reflect radio waves in the

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same manner as would any other phenomenon causing an increase in electron density. That such reflection does occur is demonstrated by the GREENHOUSE data, and it can therefore be assumed that the electrons do follow the density changes of the sound wave.

The existence of the two-hop F2 reflection which was observed at GREENHOUSE in the absence of the one-hop return may be explained as follows: the highest point of the spherical blast wave lies in a region of greater ion density than do points at lower levels, because ion density generally increases with altitude. The spherical cap formed by the blast wave, therefore, has a maximum ion density at its center, and the density falls off toward the edges. However, radio waves are retarded by passing through a region of high ion density; the spherical cap, therefore, behaves like a positive (converging) lens. If the distance from the "lens" to the earth were equal to the focal length, the rays from the C-3 recorder would be parallel after leaving the lens. These rays would be reflected from the F layer (considered flat, for simplicity) and, after passing through the lens a second time would come to a focus at the C-3 recorder, and the distance of travel of the pulses sent out by the recorder would be twice the F-layer altitude. However, if the focal length of the lens were sufficiently greater than the distance from the lens to the earth, so that the rays returning to the earth would arrive vertically instead of converging to a point, these rays would be reflected from the earth, would experience a second reflection from the F layer and would then be focussed on the earth by the lens. In this case, the travel distance would be four times the F-layer altitude and the delay would correspond to two-hop F propagation. The one-hop F return would not be observed because it would be "out of focus." This tentative explanation is purely qualitative; to put it on a quantitative basis would require detailed knowledge of the electron density at all points in the blast wave, as a function of time.

Because of the inhomogeneity of the atmosphere (which is due to turbulence, etc.), the sound wave from an atomic explosion would not be a perfectly smooth sphere, but probably would more closely resemble a thin spherical shell, with a somewhat irregular outer surface and a still more irregular inner surface. (The tail of the sound wave from an explosion is usually more irregular than the front, and oscillations with a predominant period of 10 seconds may continue, although rapidly damped, for a period of several minutes.) We would, therefore, expect fairly good reflection to occur from the outer surface of the sphere, and scattering to occur from the inner surface. As such a sphere expanded through the ionized layers, additional modes of propagation (i.e., ray paths) would be possible for radio sites outside the sphere, as indicated in Fig. 3.12 and Fig. 3.17. In addition to reflection from the upper surface, some of the energy incident upon the under side of the sphere (when such incidence is permitted by the path geometry) might be scattered back to earth even if the frequency were so high that most of the energy would penetrate the sphere, as well as the

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ionospheric layers. The theory of such scattering in the troposphere has been developed by Booker and Gordon[2] and extended by Booker and others[1] to the ionosphere.

In view of the above explanation of the results observed during the GREENHOUSE and BUSTER tests, the decision was made to supplement the vertical incidence (C-3) soundings and C-W transmissions with pulse transmissions during the TUMBLER-SNAPPER tests. By using the pulse technique at oblique incidence, the effects of the blast wave on each mode of propagation could be observed separately; furthermore, possible additional modes of propagation arising from reflections from the top of the blast wave would be detectable. The instrumentation was also designed to attempt to detect scattering by the blast of those C-W signals which would normally be of high enough frequency to penetrate the ionospheric layers. In addition to the radio propagation tests, it was planned to record the blast wave itself, in order to determine the predominant acoustical frequency present, as well as the amplitude and duration of the sound pulse, since this information might aid in the interpretation of the radio data.

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CHAPTER 2

INSTRUMENTATION AND OPERATING PROCEDURE

2.1 OUTLINE OF EXPERIMENTS

2.1.1 Vertical Incidence Sweep Frequency Soundings

Vertical incidence sweep frequency ionosphere soundings were made at the Nevada Proving Grounds and at White Sands Proving Ground.

2.1.2 Pulsed Radio Transmissions

Pulse transmissions were made over a 590-mile path, at a frequency expected to be propagated normally via both the E and F layers, with reflection points almost directly above the explosion.

2.1.3 Short Range C-W Transmissions

C-W transmissions were made over the same 590-mile path. It was planned to use frequencies which would not be propagated normally via either the E or F layer but which might be propagated by forward scatter from a possible E-layer scattering area caused by the explosion. However, because of interference on some of the assigned channels, it was necessary to use frequencies which would be transmitted by the normal modes in the case of all shots excepting No. 3.

2.1.4 Longer Range C-W Transmissions

C-W transmissions were made over 930- and 1305-mile paths, at frequencies expected to be propagated normally via the F layer, with each receiving location situated so that the wave passed through the E layer at a point near the explosion. These are the same transmissions as those listed in paragraph 2.1.3 above, but normal ionospheric propagation was expected, due to the angle of incidence being more oblique for the greater path lengths.

2.1.5 Sonic Recordings

Recordings of the blast wave were made at both ends of the radio path to form an estimate of its magnitude and shape.

2.2 INSTRUMENTATION

2.2.1 General

Equipment was installed at sites indicated on the accompany-

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ing map (Fig. 2.1) which also indicates distances between the various locations.

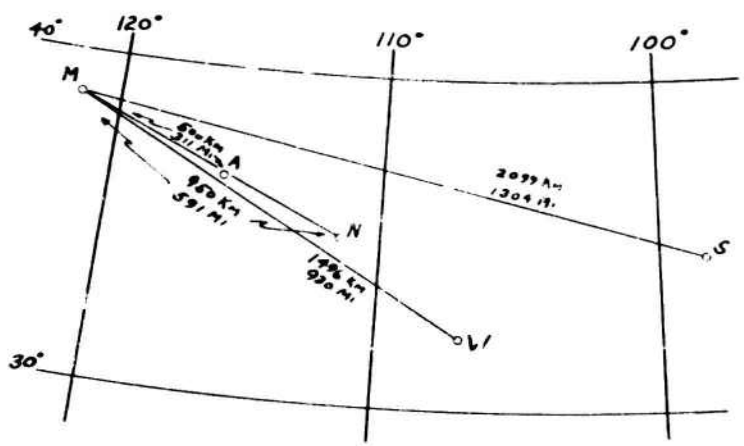

Fig. 2.1 Locations of Equipment Installation (M-Mather Air Force Base, A-Nevada Proving Grounds, N-Navajo Ordnance Depot, W-White Sands Proving Ground, S-Fort Sill)

Equipment consisted of:

Two BC-610 transmitters (one for standby) operating on CW, installed in a K-53 truck located at Mather AFB, Sacramento, California.

Two BC-610 transmitters (one for standby) modified for pulse operation, installed in a second K-53 truck located at Mather AFB, Sacramento, California.

Two BC-779 receivers (one for standby) modified for pulse reception using an oscilloscope presentation, and two BC-779 receivers (one for standby) for C-W reception using an Esterline-Angus recorder, all installed in a K-53 truck located at Navajo Ordnance Depot, Flagstaff, Arizona.

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BC-779 receivers for C-W reception using Esterline-Angus recorders, located at White Sands, N.M. and Fort Sill, Oklahoma.

A C-3 ionosphere recorder installed in a trailer located at the Nevada Proving Grounds.

The existing C-3 installation at White Sands, N.M.

Equipment at Navajo and Mather for picking up and recording the sonic waves. (See report on Operation BUSTER-JANGLE Projects 7.6B and 7.3J 4/ for description of the sonic equipment.)

2.2.2 Transmitter Site (Mather AFB)

The following equipment was installed at Mather Air Force Base, Sacramento, California:

Two BC-610 transmitters, one for CW and one for pulse, operated crystal-controlled with a power output of 400 watts CW and 400 watts peak pulse. The C-W signal was interrupted periodically to aid in its identification by personnel operating the receivers. The pulse length was 150 microseconds and the pulse repetition frequency was 100 per second.

A half-wave horizontal antenna, approximately one wavelength high at the frequencies to be used for C-W transmission.

A half-wave horizontal antenna, approximately one-half wavelength high at the frequencies to be used for pulse transmission.

2.2.3 Radio Receiving Site - (Navajo Ordnance Depot)

The following equipment was installed at Navajo Ordnance Depot, Flagstaff, Arizona:

A BC-779 receiver for pulse reception with a motion picture camera for photographing oscilloscope presentation.

A BC-779 receiver for C-W reception with output recorded on an Esterline-Angus (0-1 ma) recorder.

Antennas similar to those at the transmitting site.

2.2.4 Radio Receiving Site - (White Sands Proving Ground)

A BC-779 receiver with a 13-mc horizontal doublet antenna 90 feet high was used for C-W reception at White Sands Proving Ground, N.M., and data were recorded on an Esterline-Angus (0-1 ma) recorder.

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2.2.5 Radio Receiving Site - (Fort Sill)

A BC-779 receiver with a whip antenna was used for C-W reception at Ft. Sill, Oklahoma and data were recorded on an Esterline-Angus (0-1 ma) recorder.

2.2.6 Sonic Receiving Site - (Navajo Ordnance Depot)

A low frequency microphone, amplifier and Esterline-Angus recorder were installed at Navajo Ordnance Depot.

2.2.7 Sonic Receiving Site - (Mather Air Force Base)

The sonic equipment installed at Mather AFB was identical with that at Navajo.

2.3 OPERATING PROCEDURE

On the day preceding each atomic explosion, a "dry run" was made to determine the best frequency for pulse operation. For this dry run, the pulse transmitter frequency was changed every 10 minutes for a 2 hour period centered about the expected time of the blast. Three frequencies were used for this test, one near the predicted optimum frequency, one about 1 mc above and one about 1 mc below this value.

Listening tests were made on the various frequencies assigned for C-W transmission and the frequency was selected according to the amount of interference present on the various channels. Following the dry run, personnel at the transmitter and at the various receiving sites were instructed regarding the frequency choice.

On the day of the test, the pulse and C-W transmitters were operated from minus 1 hour to plus 2 hours. The pulse receiver output was monitored on two oscilloscopes, one for visual observation and one for motion picture recording. However, the camera was operated only from minus 5 minutes to approximately plus 30 minutes. The C-W receiver output was recorded by means of Esterline-Angus recorders operating at 6 inches per minute.

Sonic equipment was operated on the day of the test from minus 1 hour to plus 2 hours.

Records from the various sites were sent to Evans Signal Laboratory, where the films were processed and results evaluated. In evaluating the results, it was found necessary to run the films repeatedly through a motion picture projector in order to discover any rapidly

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changing effects which could be ascribed to the blast. The films were then subjected to a detailed frame-by-frame examination and a selection was made of a series of individual frames which best illustrated the sequence of events which had been observed during the cinematographic projection.

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CHAPTER 3

RESULTS

3.1 SHOT TIMES AND TRANSMISSION FREQUENCIES

Table 3.1 gives the dates and times of the shots to the nearest minute, as well as the approximate frequencies used for both C-W and pulsed radio transmissions. Unless otherwise stated, all times given in discussing the results are referred to these nominal shot times; with one exception these times are correct within 3 seconds, which represents a relatively small error in the time intervals with which we are concerned (6 to 10 minutes).

TABLE 3.1

Shot Dates, Times and Radio Transmission Frequencies

Shot	Date	Shot Time (Z Time)	C-W Frequency (megacycles)	Pulse Frequency (megacycles)
1	1 April 52	1700	13	7
2	15 April 52	1730	13	8
3	22 April 52	1730	13	7
4	1 May 52	1630	11	6
5	7 May 52	1215	11	7
6	25 May 52	1200	13	5
7	1 June 52	1155	12	5
8	5 June 52	1155	12	5

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3.2 VERTICAL INCIDENCE IONOSPHERIC SOUNDINGS

3.2.1 General

No effect of the shots was observed on the ionospheric sounding records taken at White Sands. These records were used to verify and supplement information obtained at the Nevada Proving Grounds concerning normal ionospheric conditions on the shot days.

Results of the vertical incidence ionospheric soundings taken at the Nevada Proving Grounds are shown by selected photographs of the oscilloscope traces in Fig. 3.2 through Fig. 3.10. Equipment difficulties are responsible for the absence of pictures from Shots 2 and 6.

In general, the earliest picture shown for each shot represents normal conditions either prior to the time of the blast or prior to any observable effect of the shot. Interference from other radio signals marred all records (except those for Shots 1 and 4) and, very unfortunately, was worst for Shot 3, obliterating much of what appears to be the most interesting series of pictures.

3.2.2 Frontal Effect in E Region

The first four shots took place several hours after sunrise, and consequently, the E layer was well established. For each of these shots (except No. 2, for which no pictures were obtained), an E-layer effect was observed near the critical frequency at about the same time after zero. A somewhat different type of effect occurred at approximately the same time after Shot 7, a pre-dawn explosion. In each case, the effect observed was the earliest one which was apparently due to the shot, and the effect occurred prior to the normal sonic arrival time. It is believed that the effect was caused by the arrival of the shock front in the E region and it will, therefore, be called the "frontal effect." However, because of entirely different ionospheric conditions existing on each of these four shot days, the manifestations were all different, as will be discussed in paragraphs 3.2.5, 3.2.6, 3.2.7 and 3.2.9 below, shot by shot.

Table 3.2 lists the times and heights; the times are compared with the normal sonic travel time computed from rocket flight data as presented in Appendix C to the report on Project 6.., Operation BUSTER.[1]

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TABLE 3.2

Time of Occurrence of Frontal Effect in E Region

Shot	Time (from Zero)	Approx. Height (km)	Normal Sonic Travel Time	Time Ahead of Normal (sec)
1	5' 38"	110	6' 00"	22
3	5' 20"	105	5' 45"	25
4	5' 17"	105	5' 45"	28
7	5' 22"	110	6' 00"	38

The apparent arrival of the shock wave ahead of the normal travel time corroborates qualitatively the theoretical discussion of the sonic velocity in Paragraph 3.5 of this report, but should not be used quantitatively, because of the inaccuracies of all parameters.

3.2.3 <u>Lagging Effect in E Region</u>

The second effect which had a common denominator among several shots was an effect which occurred in the E region about 30 seconds after the frontal effect. It consisted of a horizontal line extending far beyond the E-layer critical frequency and had the appearance of the usual sporadic-E return. Its height increased at approximately sonic velocity. The time of occurrence and the apparent velocity seem to link the effect with the "tail" of the shock wave, since the front travels faster than normal sonic velocity (as discussed in Paragraph 3.5 of this report). An additional fact worthy of note is that the highest frequency returned seems to have attained a maximum at about the time the reflection reached the height of maximum electron density of the E layer. The data concerning the lagging effect are summarized in Table 3.3.

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TABLE 3.3

Time of Occurrence of Lagging Effect in E Region

Shot	Time (from Zero)	Approx Height (km)	Normal Sonic Travel Time	Time Behind Normal (sec)	Highest Freq Returned (mc)
1	6' 16"	105	5' 45"	31	3.2
	6' 39"	110	6' 00"	39	[illegible]
	6' 55"	120	6' 27"	28	7.0
	7' 10"	125 *	6' 39"	31	6.6
	7' 41"	135	7' 04"	37	5.6
				Avg - 33	
3	6' 05"	100	5' 28"	37	4.7
	6' 13"	105	5' 45"	28	[illegible]
	6' 28"	110	6' 00"	28	5.9
	6' 43"	113 *	6' 13"	30	7.6
	6' 58"	120	6' 27"	31	5.9
	7' 13"	125	6' 39"	34	5.9
	7' 50"	140	7' 15"	35	5.8
	7' 54"	145	7' 20"	34	5.3
	8' 13"	150	7' 36"	37	5.5
				Avg - 32	
4	6' 10"	105	5' 45"	25	6.9
	6' 25"	110 *	6' 00"	25	6.9
	6' 32"	112	6' 05"	27	6.8
	7' 10"	125	6' 39"	31	5.6
	7' 25"	130	6' 51"	34	5.6
	7' 40"	135	7' 04"	36	5.8
				Avg - 30	
7	6' 08"	113	6' 07"	1	5.8
	6' 15"	115 *	6' 13"	2	6.0
	6' 22"	118	6' 21"	1	5.7
	6' 30"	120	6' 27"	3	6.3
				Avg - 2	

* Approximate height of maximum electron density

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As mentioned in Paragraphs 1.2.1 and 1.2.2 of this report, a similar effect was observed in C-3 records of GREENHOUSE George shot and BUSTER Dog and Easy shots. A table has been prepared from available records of these tests and is presented below for comparison.

TABLE 3.4

Time of Occurrence of Lagging Effect in E Region (GREENHOUSE and BUSTER)

Shot	Time (from Zero)	Approx height (km)	Normal Sonic Travel Time	Time Behind Normal (sec)	Highest Freq Returned (mc)
GREEN-HOUSE George	7' 30" 8' 00" 8' 30" 9' 00" 9' 15" 9' 45" 10' 00"	113 122 128 135 140 150 155	6' 07" 6' 32" 6' 46" 7' 04" 7' 15" 7' 36" 7' 46"	83 88 104 116 120 129 134 Avg - 111	8.8 10.0 8.7 8.6 8.3 8.1 7.8
BUSTER Dog	7' 00" 7' 22" 8' 00" 8' 30"	115 120 125 130	6' 13" 6' 27" 6' 39" 6' 51"	47 55 81 99 Avg - 70	5.6 6.5 5.5 5.8
BUSTER Easy	6' 45" 7' 15" 8' 45" 9' 30"	105 115 140 155	5' 45" 6' 13" 7' 15" 7' 46"	60 62 90 104 Avg - 79	7.5 7.3 6.1 6.0

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The time lag behind the normal sonic time appears to have been greater for the GREENHOUSE and BUSTER tests than for TUMBLER-SNAPPER tests. This may have been due to different conditions in the lower atmosphere, different ionospheric conditions, different characteristics of the sonic wave, or a longer "tail" on the sonic wave. A time lag increasing with height of the return is evident in the data for each test given in Table 3.4 and there may be a similar tendency in the data of Table 3.3 for TUMBLER-SNAPPER shots, particularly No. 4. The cause of this phenomenon is not yet understood.

3.2.4 Effects in the F Region

The effects observed in the F region, which will be described in detail later, may best be explained by reference to Fig. 3.1.

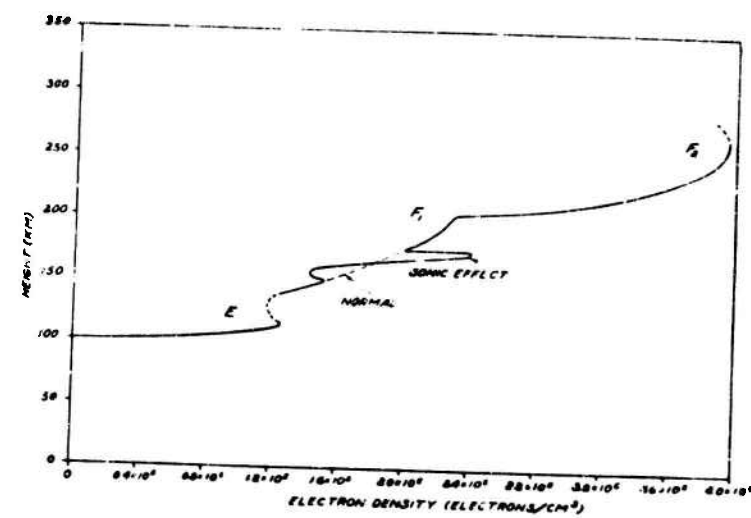

Fig. 3.1 A Typical Electron Density Distribution Curve with Sonic Effect Superimposed

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The normal distribution curve shown in the figure was calculated from the vertical incidence record at 14 minutes 10 seconds before Shot 3 (first picture in Fig. 3.3), using the Booker and Seaton method3. The superimposed sonic effect was arbitrarily placed for illustrative purposes. It is apparent that, as the shock wave moves upward, the condensation and rarefaction associated with it will result in strata of increased and decreased electron density as illustrated. This in turn, will cause the appearance of a cusp, or partial cusp on the trace of the vertical incidence record, similar to the cusp which appears when the normal F layer splits into the F1 and F2 layers. The rising sonic wave will cause a progressive increase in the frequency at which the cusp appears, since the electron density is greater at higher altitudes; hence, the frequency returned is greater. Another effect to be expected is a temporary increase in the critical frequency of the layer when the sonic wave front reaches the region of maximum electron density. These effects can be seen by following through the picture sequences for Shots 3, 5 and 7, as described in more detail in paragraphs 3.2.6, 3.2.8 and 3.2.9. Similar affects were observed for Dog and Easy shots of Operation BUSTER.

The height of the sonic wave cannot be measured directly from its effects in the F region. One reason for this is that the actual height of reflection from the F layer varies considerably with frequency ever without the distortion of the electron distribution introduced by the sonic wave. Secondly, the C-3 recorder does not record actual height but only indicates the virtual height of reflection, which is proportional to the travel time of the radio pulse and is based upon the incorrect assumption of constant velocity equal to that in free space. Consequently, it is an extremely difficult problem to try to ascertain the true height of the sonic wave which is responsible for a particular cusp in the F-layer return. However, one point can be located by determining approximately when the frequency of the cusp which is due to the sonic wave has reached the critical frequency of the layer. It is assumed that the sonic wave then approximately coincides with the height of maximum electron density of the layer, as determined by the Booker and Seaton method from a record taken just prior to any shot effect. These estimates are given in Table 3.5. In each case, it is seen that the average travel velocity is somewhat greater than the average normal sonic velocity. A detailed discussion of this phenomenon is given in paragraph 3.5 below, under the heading Sonic Recordings. (Data for Shot 6 appearing in Table 3.5 were obtained from 16 mm motion pictures.)

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TABLE 3.5

Approximate Time of Sonic Wave Arrivals at Height of F-Layer Maximum Electron Density

Shot	Time (from Zero)	Approx Height of Max. Electron Density (km)	Normal Sonic Travel Time
1	7' 45"	200	9' 09"
3	9' 13" * 11' 30"	260	10' 52"
5	13' 00"	385	13' 45"
6	12' 30"	345	12' 58"
7	11' 55"	340	12' 50"
8	13' 00"	375	13' 35"
Dog (BUSTER)	8' 15" * 10' 00"	260	10' 52"
Easy (BUSTER)	8' 45" * 10' 15"	240	10' 20"

* Second Arrival

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3.2.5 Shot 1 (Fig. 3.2)

The pre-effect picture at 5 minutes 23 seconds shows a thick E layer with critical frequency of 3.0 mc, an F1 layer at a virtual height of 210 km obscuring the F2 layer (because the F1 critical frequency of 3.9 mc was greater than that of the F2 layer), a portion of two-hop F1, and part of the extraordinary F1 trace (critical frequency about 4.6 mc). At 5 minutes 38 seconds, there was a possible faint indication of frontal effect of the sonic wave at 110 km (3. to 3.2 mc). It became more definite at 5 minutes 45 seconds (picture not shown); by 5 minutes 53 seconds the sonic wave caused two horizontal lines at about 115 and 125 km. From then on, the remaining pictures show many reflections in this region just below E-layer critical frequency. The lagging effect, producing traces which had an appearance similar to sporadic E, began at 6 minutes 16 seconds at 105 km and continued with increasing height through 7 minutes 41 seconds, at which time it had reached 135 km. From 7 minutes 26 seconds on, there appeared to be a strong sporadic-E trace at 100 km which may or may not have had any connection with the shot. The sporadic E at 115 km at 8 minutes 21 seconds continued for about 45 seconds more, and may have been normal.

At 7 minutes 26 seconds, the F1-layer trace was broken up by the shock wave, which was at that time at a height somewhere between 160 and 190 km. The extraordinary trace was similarly broken and there may have been a slight increase in critical frequency of both traces. At 7 minutes 41 seconds and at 7 minutes 49 seconds both the ordinary and the extraordinary traces were flattened. At 8 minutes 5 seconds the picture is seen to be returning to normal, but there is still an effect on the shape of the F-layer traces. The 8 minutes 21 seconds picture is more or less normal.

3.2.6 Shot 3 (Fig. 3.3 through Fig. 3.6)

The pre-shot picture at minus 15 minutes 10 seconds is the picture from which the electron density curve of Fig. 3.1 was calculated. The absence of interference presents an interesting contrast to the tremendous amount which was present after the shot. In the pre-shot picture, the E-layer critical frequency was 3.1 mc, the F1 ordinary was 4.3 mc and the F2 ordinary was 5.6 mc; in addition, a portion of the F1 extraordinary trace and all of the F2 extraordinary trace could be seen.

[redacted]

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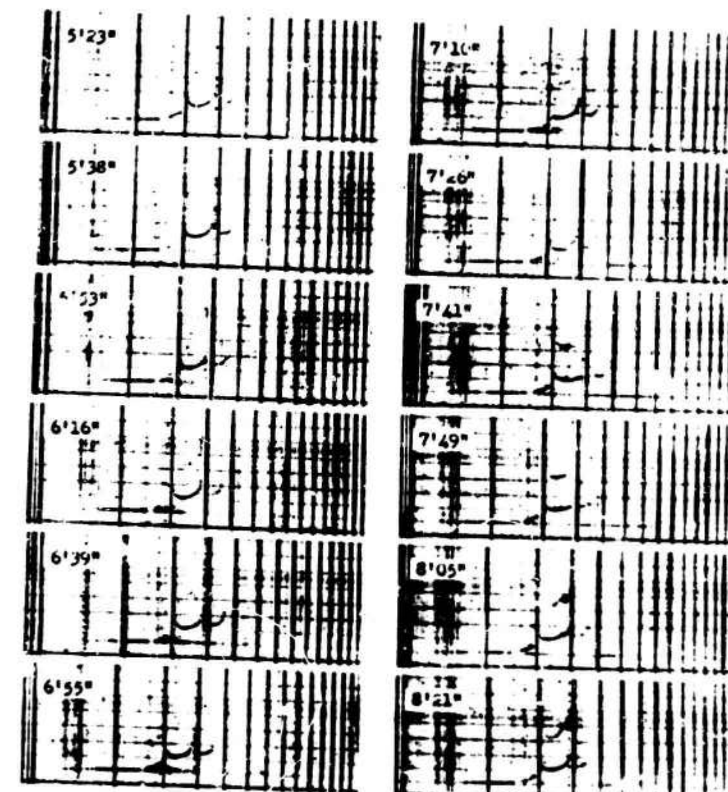

Fig. 3.2 Ionospheric Records, Shot 1 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

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At 5 minutes 20 seconds a faint indication of the arrival of the shock front could be seen at 105 km (2.4 to 2.[illegible] mc). Thereafter, from 5 minutes 28 seconds through 5 minutes 43 seconds, the E-layer trace which was absent, probably because of absorption, returned, became stronger, and apparently rose with sonic velocity. Then, starting at 5 minutes 50 seconds and continuing through 7 minutes 5 seconds, the same type of break-up of the E layer that was described above for Shot 2 occurred at frequencies just below the critical frequency. Many of these lines may have been due to oblique reflections from the shock front. After 7 minutes 5 seconds, a similar break-up occurred in the portion of the F1 trace not obscured by interference, continuing until 10 minutes 13 seconds.

At 7 minutes 43 seconds, a segment of what is probably the F1 extraordinary trace emerged from the interference at 5 mc. Its critical frequency increased, and the segment rose through the F2 region. After the critical frequency had increased [illegible] mc at 8 minutes 43 seconds, interference prevented any further determination of its value.

At 8 minutes 20 seconds another trace emerged from the interference with a cusp just above 5 mc. It was probably the F2 ordinary trace, since the higher portion of F2 ordinary, seen between 5 and 6 mc, exhibited an upturn at the left end. The cusp moved to higher frequencies until 8 minutes 43 seconds. Then the F2 ordinary critical frequency increased from 5.7 mc to 5.8 mc at 9 minutes 13 seconds, to 5.9 mc at 9 minutes 28 seconds, and to 6.0 mc at 9 minutes 35 seconds, where it either remained or moved to higher frequencies and became hidden by interference. At 10 minutes 13 seconds, a new cusp appeared which progressed from 5.2 mc at 10 minutes 28 seconds to 5.7 mc at 11 minutes 5 seconds, and finally merged with the upturn at the critical frequency of the F layer at 5.9 mc when conditions began to return to normal at 11 minutes 35 seconds.

Effects which are not theoretically accounted for took place from plus 17 to plus 22 minutes. At 17 minutes 13 seconds, the F1 trace had a peculiar shape; at 17 minutes 58 seconds, the trace had vanished, at 18 minutes 5 seconds the trace appeared with a normal shape, vanished again at 21 minutes 20 seconds, returned at 21 minutes 28 seconds and disappeared again at 21 minutes 35 seconds. During this time, changes in shape also occurred in the F2 traces. The final picture taken at 21 minutes 43 seconds shows the trace after all apparent effects of the blast had disappeared.

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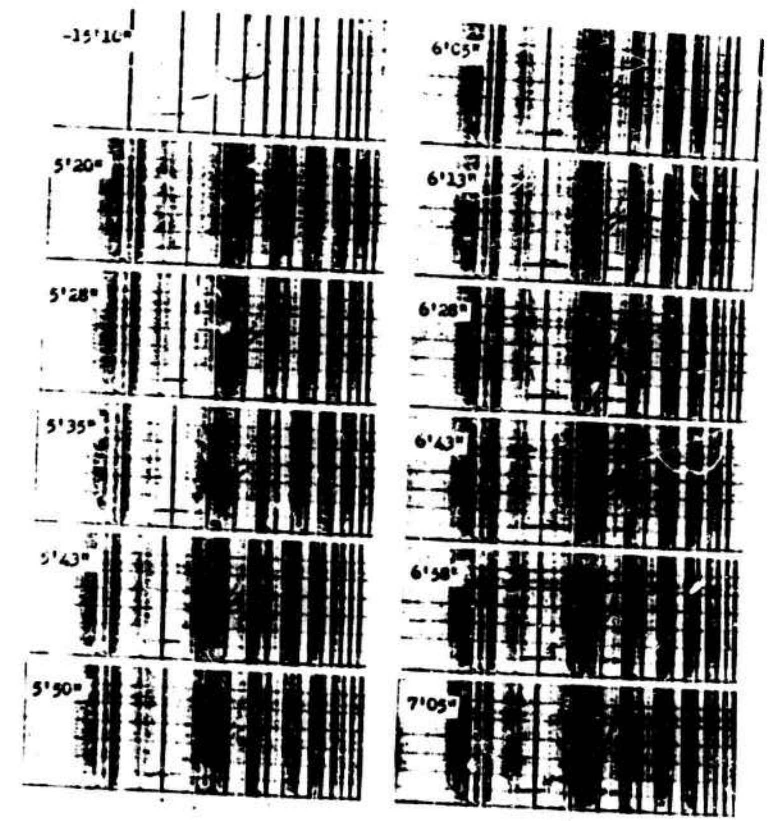

Fig. 3.3 Ionospheric Records, Shot 3 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

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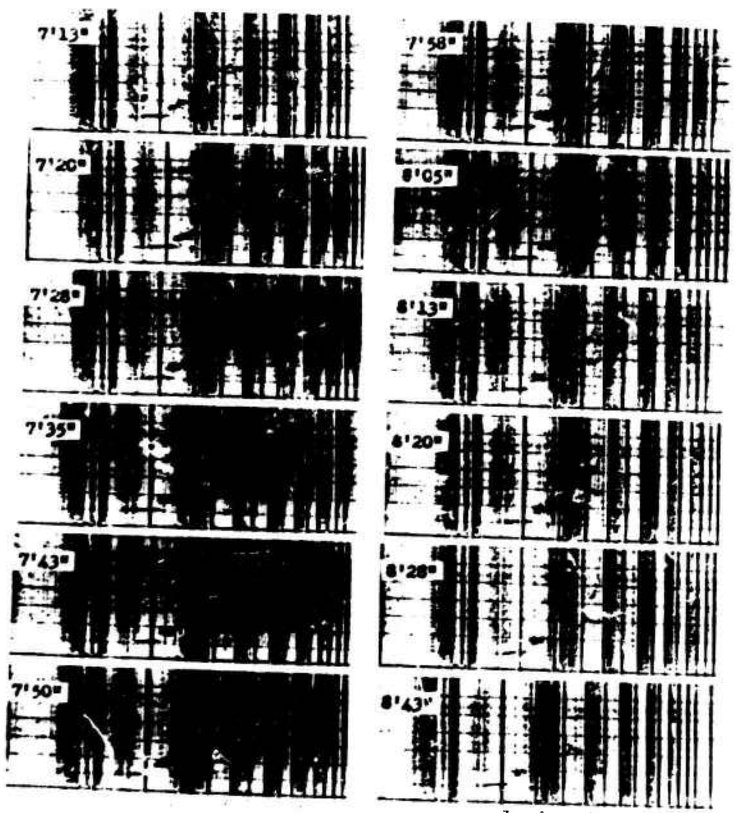

Fig. 3.4 Ionospheric Records, Shot 3, Continued (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

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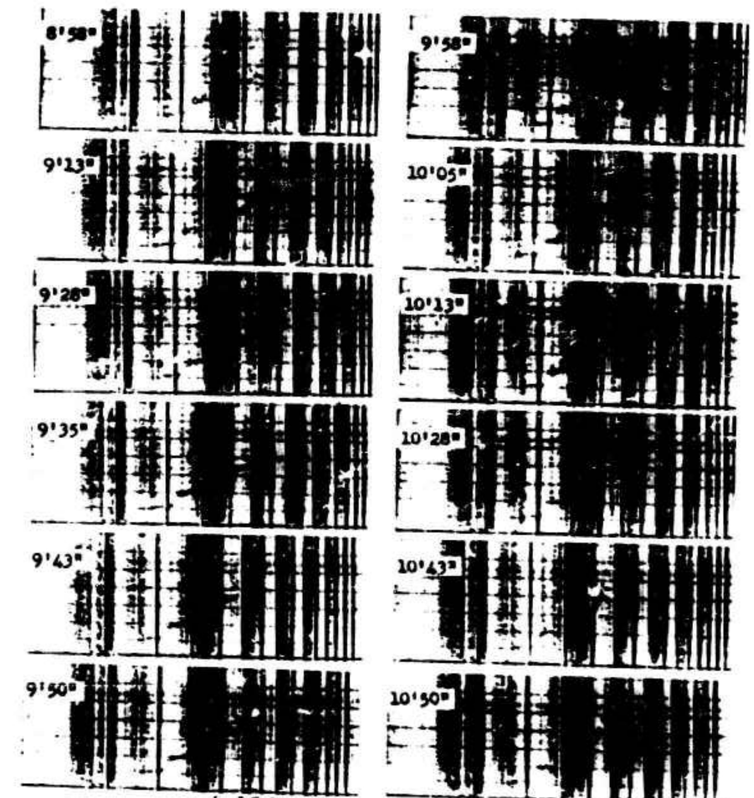

Fig. 3.5 Ionospheric Records, Shot 3, Continued (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

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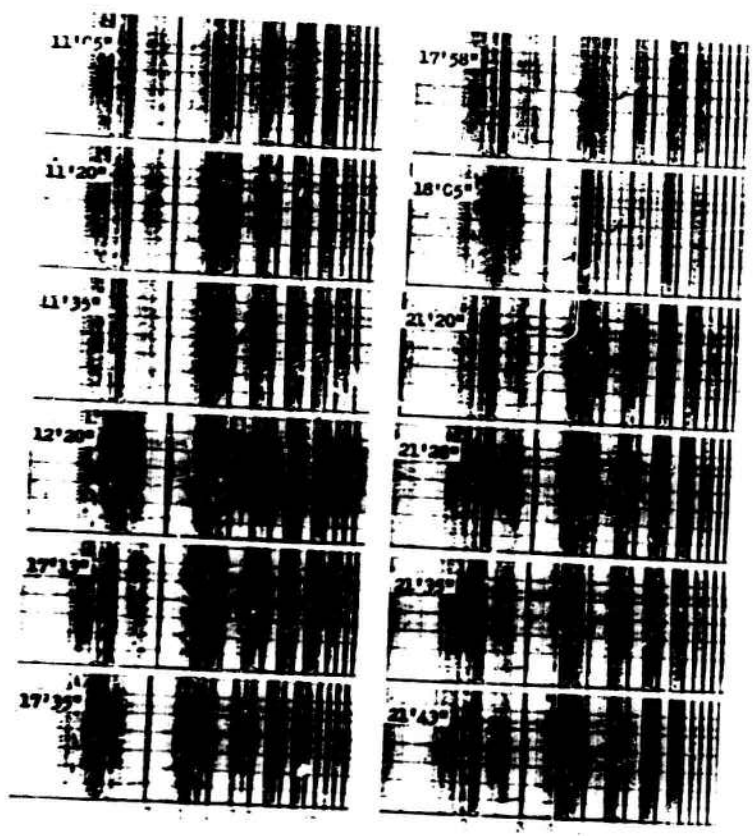

Fig. 3.6 Ionospheric Records, Shot 3, Continued (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

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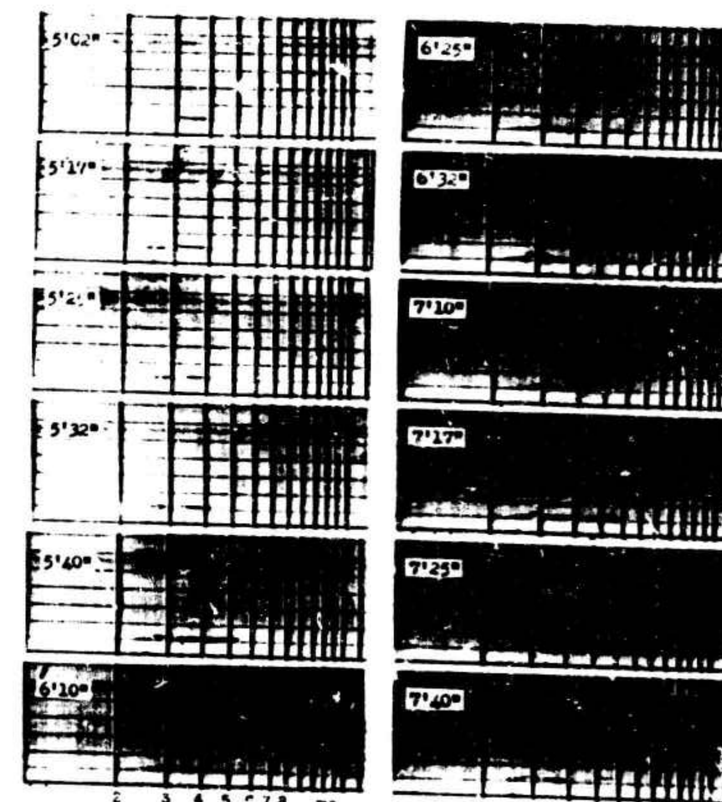

Fig. 3.7 Ionospheric Records, Shot 4 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

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3.2.7 Shot 4 (Fig. 3.7)

An ionospheric storm was in progress on this day and an unusual blanketing type of sporadic E was present before and during the test. It is assumed that an E layer, with a critical frequency of about 3.0 mc would have shown up at 5 minutes 2 seconds, but for absorption in regions below it. However, at 5 minutes 17 seconds, the arrival of the shock wave appears to have strengthened the E-layer reflection sufficiently to overcome the absorption. Extensions of the existing sporadic-E traces to higher frequencies were visible beginning at 6 minutes 10 seconds. A portion of the sporadic-E trace between 5 and 6 mc rose with sonic velocity as listed in Table 3.3.

3.2.8 Shot 5 (Fig. 3.8)

At minus 22 minutes, the normal pre-shot picture is seen, with typical pre-dawn conditions: no E layer was present and the F layer had not yet split into F1 and F2. The critical frequency was 2.1 mc for the ordinary F trace and 2.8 mc for the extraordinary F trace. From 9 minutes 38 seconds to 10 minutes 8 seconds, partial cusps moved across both the ordinary and extraordinary traces, the effect apparently reaching the height of maximum electron density (about 38[illegible] km) at about 10 minutes 8 seconds. The cause of this early effect ($3\frac{1}{2}$ minutes ahead of normal sonic travel time) which was much weaker than the later effect, is not understood.

From 11 minutes 30 seconds to 12 minutes 45 seconds, a definite stratification moving up through the F layer caused the trace to have a cusp with the following critical frequencies (in mc):

11' 30"	1.75
11' 45"	1.95
12' 00"	2.05
12' 15"	2.1[illegible]
12' 30"	2.2[illegible]
12' 45"	2.23

The F-layer critical frequency remained at about 2.35 mc throughout the above cusp movement, the upper segment having a steep upturn toward the left because of retardation at frequencies near those of the moving cusp.

[redacted]

[redacted]

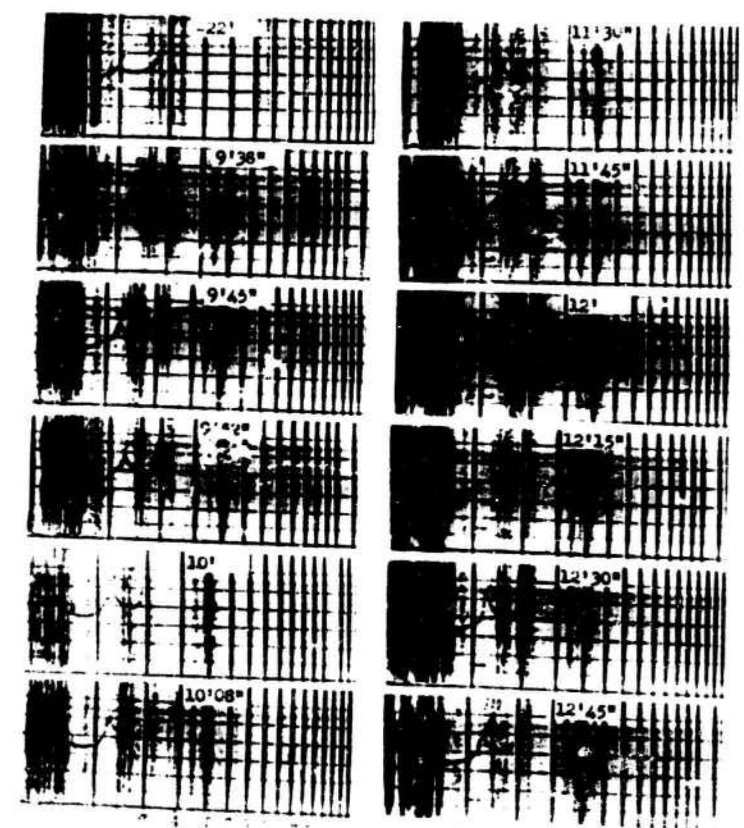

Fig. 3.8 Ionospheric Records, Shot 5 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

[redacted]

3.2.9 Shot 7 (Fig. 3.9)

In the picture made at plus 5 minutes (before any shot effects were noticeable), there was a typical pre-dawn F layer and some sporadic E in two segments. The shock front apparently caused a sudden increase in the upper frequency limit of the existing sporadic E at 5 minutes 22 seconds; the front appeared independently at a higher level at 5 minutes 30 seconds and still higher at 5 minutes 38 seconds. Then, at 6 minutes 8 seconds, the type of sporadic E, described in paragraph 3.2.3 as the lagging effect, commenced, rising until 6 minutes 30 seconds (pictures taken at 6 minutes 15 seconds and 6 minutes 30 seconds not shown).

The normal critical frequencies of 2.8 mc (ordinary) and 3.5 mc (extraordinary) each increased by about 0.1 mc at 10 minutes 37 seconds and 10 minutes 59 seconds, as the typical F-layer effect of cusps moving to the right began. The moving critical frequencies (in mc) were:

10' 37"	-		-	2.3	(ext)
10' 59"	-	1.9 (ord)	-	2.7	(ext)
11' 13"	-	2.0 (ord)	-	2.9	(ext)
11' 27"	-	2.2 (ord)	-	3.05	(ext)
11' 41"	-	2.45 (ord)	-	3.2	(ext)

3.2.10 Shot 8 (Fig. 3.10)

The pictures of this shot are not particularly good, since "spread echoes" were present, and have been included only for completeness. Sporadic E occurring from 4 minutes 38 seconds to 5 minutes 22 seconds may have been normal or may have been caused partly by the shot. From 11 minutes 45 seconds to 13 minutes spread echoes obliterated most of the effect, though some cusp formation could be seen.

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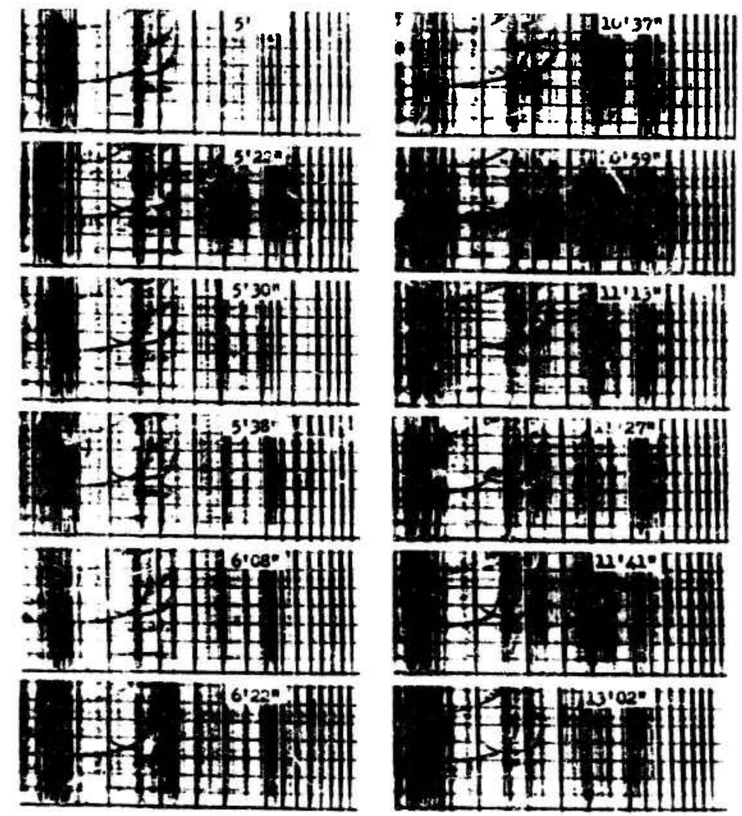

Fig. 3.9 Ionospheric Records, Shot 7 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

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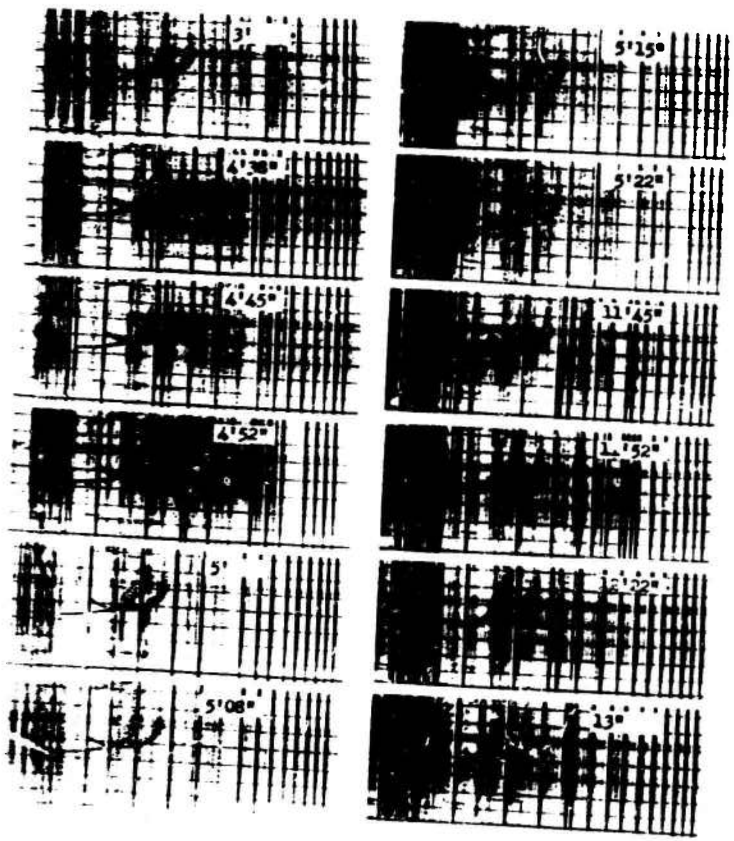

Fig. 3.10 Ionospheric Records, Shot 8 (Horizontal lines are height markers at 100 km intervals, the heavy line near the bottom being the ground trace.)

[redacted]

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3.3 PULSE TRANSMISSIONS

Because the first shot was detonated half an hour earlier than schedule, the pulse receiver was not in operation and no record was obtained. Severe radio interference was present during most of the other tests; no data of value were obtained on Shots 2, 4, 5 and 8 because of particularly bad interference. Best results were obtained on Shot 3, but on Shots 6 and 7, the signal pips could be seen through gaps in the interference and it was possible to make a decision regarding the presence or absence of any effects due to the bomb.

3.3.1 Shot 2

The first picture of Fig. 3.11 shows the appearance of the pulse just before the blast. The first pulse seen (in the group near the center of the trace) is a composite of the E, F1 and F2 returns, which are recorded as one pulse because the reflection from the E layer is so much stronger that it masks the F1 and F2 signals. The next pulse, barely visible above the noise level, has been identified as the two-hop F2 return, and the third pulse, about half the amplitude of the first one, is probably the F2 Pedersen ray (a ray which leaves the transmitter at a much steeper angle than the lower F2 ray and is, therefore, greatly retarded because it spends a larger portion of its time in a region of high ion density). The next pulse group is merely a repetition of the first group, with a separation corresponding to the pulse interval of 10,000 microseconds.

The second picture, taken at plus 5 minutes 43 seconds, shows a sudden fade of the E return; at this time, the blast wave was traveling through the E layer and the fade undoubtedly occurred just as the compressional wave front became tangent to the E-layer ray, causing the latter to deviate. During the fade of the E-layer pulse, those modes which it had previously masked (F1 and F2) became visible. A few seconds later, the E pulse reappeared (third picture) and at the same time, a particularly strong signal appeared at approximately the expected position of the F2 return. This may have been a regular F2 reflection, or it may have been a ray which was first reflected from the blast wave and then from the F2 layer, since such a pulse would have about the same travel time as an F2 pulse. For a minute or so, this signal faded in and out rapidly, indicating that it may have been a reflection of the type just described, which alternately reinforced and interfered with the regular F2 pulse.

From plus 7 minutes on, additional modes appeared which gradually blended into a continuous band of arrivals, the band itself widening until it attained a maximum extent corresponding to a time

[redacted]

interval of 2.5 milliseconds at plus 8 minutes (fourth picture of Fig. 3.11). This continuous band of arrivals is attributed to the existence of a large number of additional modes of propagation resulting from reflections from the blast wave; some of the possible reflections are indicated in Fig. 3.12, (which is not drawn to scale).

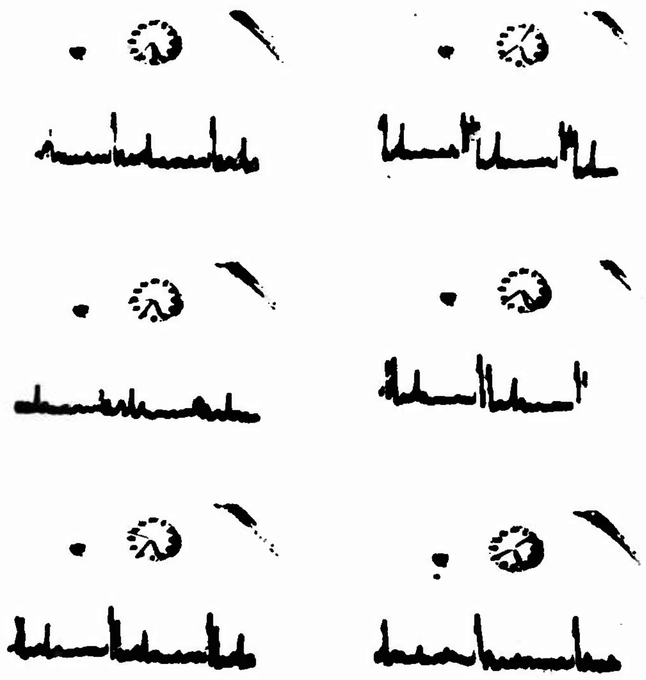

Fig. 3.11 Pulse Signals, Shot 3

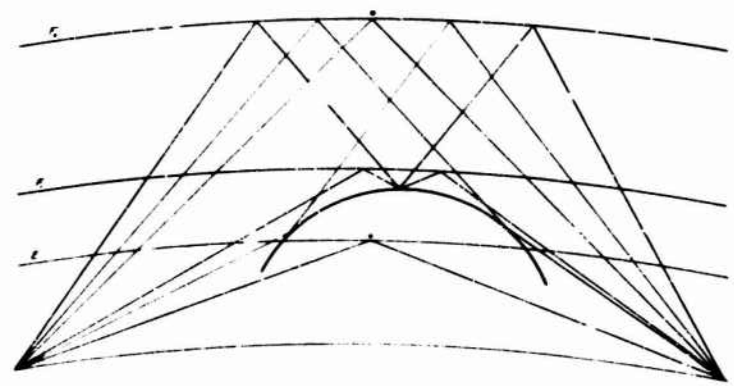

Fig. 3.12 Possible Ray Paths, Mather to Navajo, Showing Reflection from Blast Wave (Normal modes are indicated by *.)

At approximately plus 8 minutes 22 seconds, these additional modes suddenly disappeared and the configuration became as shown in the fifth picture of Fig. 3.11. The first pulse is again the E, F1 and F2 modes, (all combined into a single strong pulse). The second pulse is one at approximately the position of the two-hop F1 return, but which gradually shifted to the right, relative to the other arrivals, indicating that it may have been a reflection from the under side of the blast wave. The third pulse is probably the F2 Pedersen ray. At plus 10 minutes, the second and third pulses have disappeared and the appearance of the pulse is that shown in the final picture of Fig. 3.11, which is the same as the pre-shot picture, excepting for the absence of the Pedersen ray. The Pedersen ray is not believed to have any connection with the blast as it did not reappear later.

3.3.2 Shot 6

The first picture in Fig. 3.13 shows the pre-shot signal. The first pip in the pulse group has been identified as the one-hop F return and the second one as the two-hop F return. No effect was observed until plus 12 minutes, when new modes appeared which interfered with the one-hop F pulse, causing it to fluctuate. A few seconds later these new modes had filled in the space between the one-hop and two-hop F returns, as shown in the second picture (the pip preceding the one-hop

[redacted]

F is probably sporadic E, which had just put in an appearance on the ionospheric record about this time). About a minute after the appearance of the extra modes, they disappeared again. The appearance of these extra modes coincided in time with a disturbance of the vertical incidence F trace, and the effect was undoubtedly due to reflection from the under side of the blast wave, as it passed through the F region.

Fig. 3.13 Pulse Signals, Shot 6

3.3.3 Shot 7

Figure 3.14 shows the pre-shot picture and a typical post-shot picture (taken at plus 7 minutes). The latter represents the trace at all times when not obscured by interference. Only one pulse, the F-layer return, is visible in both pictures. No effect attributable to the blast was observed during the brief intervals when the pulse was visible through the interference.

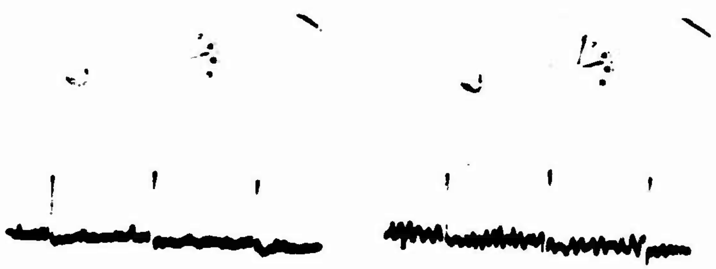

Fig. 3.14 Pulse Signals, Shot 7

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3.4 C-W TRANSMISSIONS

3.4.1 Shot 1

Since this shot occurred ahead of schedule, no equipment was in operation except that at Fort Sill, which had been turned on for a preliminary test. This receiver was operating until plus 10 minutes, when it was disconnected from the antenna for calibration. There is a definite indication of an effect starting about a minute before the receiver was turned off; the effect consisted of a sudden increase in the frequency of fading, similar to that noticed in connection with the later shots.

3.4.2 Shot 2

At Fort Sill, a definite effect on the received signal was observed starting at plus 6 minutes 35 seconds. The effect, which is shown in Fig. 3.15 consisted of a high-frequency fading superimposed upon the slower normal fading which is due to interference between the magnetoionic components. This high-frequency fading was at first quite regular, with a period of about 0.4 seconds; the period gradually increased, and as it did so, it became increasingly difficult to distinguish the fading caused by the blast from the normal fading. For the same reason, it is difficult to say exactly how long the phenomenon lasted; however, for the signal shown in Fig. 3.15, it seems to have lasted about a minute. (The sudden drop in signal a little after plus 9 minutes is the break introduced in the transmitted signal for identification.)

Fig. 3.15 C-W Signal at Fort Sill, Shot 2

[redacted]

[redacted]

At Navajo, equipment difficulty prevented the receiver from being turned on until a little after plus 7 minutes, and the beginning of the effect was probably missed. However, as shown in Fig. 3.16, rapid fading was observed from the time the equipment was turned on until about plus 9 minutes. The fading attained a maximum at about plus 7.8 minutes and then rapidly died out.

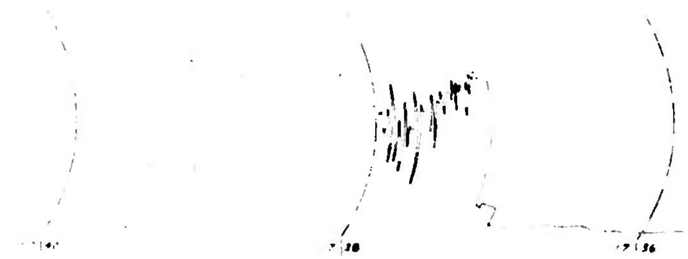

Fig. 3.16 C-W Signal at Navajo, Shot 2

The phenomenon observed is obviously a beat between two signals arriving by different paths with a gradually decreasing path difference which causes the period of the beats to become longer. Such a situation could arise from a reflection of the signal from the top of the blast wave, as shown in Fig. 3.17. Interference between this reflected signal and the normal F2 returns as the blast wave expands would produce the effect observed.

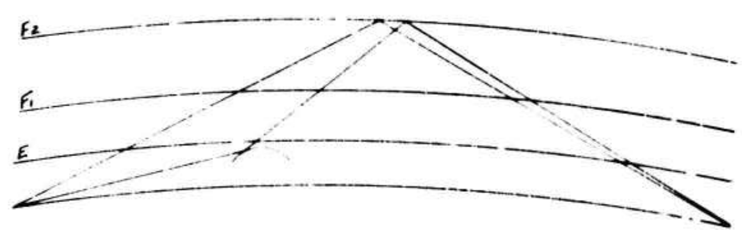

Fig. 3.17 Possible Ray Paths, Mather to White Sands, Showing Reflection from Blast Wave

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Fig. 3.18 C-W Signal at Fort Sill, Shot 3

Fig. 3.19 C-W Signal at Navajo, Shot 3

3.4.3 Shot 3

At Fort Sill, the effect described above in connection with Shot 2 was again observed, starting at plus 5 minutes 5[illegible] seconds. As before, the duration was somewhat difficult to determine exactly, but it was at least five minutes. Fig. 3.18 is a section of the Fort Sill record.

At Navajo, the C-W frequency chosen was above the MUF for the path and would not normally be received. The recorded trace in Fig. 3.19, therefore, represents the noise level (plus any interference on the channel being used). However, at plus 6 minutes, the recorded level increased for about a minute and a half, after which it returned to its previous level. This increase may have been due to scattering of the signal from the blast wave by means of the mechanism described by Bailey et al 1/. However, it is impossible to identify definitely the observed effect with the presence of a signal from the transmitter because none of the signal breaks which were introduced for this purpose occurred during the interval in question.

3.4.4 Shot 4

Effects similar to those previously observed were recorded at all three receiving sites on Shot 4. The effect was first noticed at plus 5 minutes at Navajo, plus 5 minutes 51 seconds at White Sands, and at plus 6 minutes 12 seconds at Fort Sill. The corresponding records are shown in Figs. 3.20, 3.21 and 3.22. The onset of the effect was barely detectable on the Fort Sill record and probably can not be seen in the reproduction. Reference to the map (Fig. 2.1) will show that the transmission path to Fort Sill did not pass directly over the blast; the effect of the blast, therefore, was somewhat delayed. Differences in arrival times at various stations are probably due to a combination of path geometry and signal strength effects.

3.4.5 Shots 5, 6, 7 and 8

Because of interference or failure to identify the signal, no records were obtained during these tests at locations other than Navajo, and no effects which could be attributed to the blast were found on the Navajo records. The absence of an observable effect with this series of shots can be attributed to the fact that they occurred so early in the morning that no E or F1 layer was present. By the time the blast had reached the F2 layer, it was already considerably attenuated. Furthermore, the path difference between a normal mode and a ray reflected from a blast at the height of the F2 layer would be too small to produce a high-frequency beat, and beats of lower frequency would not be distinguishable from the normal fading.

Fig. 3.20 C-W Signal at Navajo, Shot 4

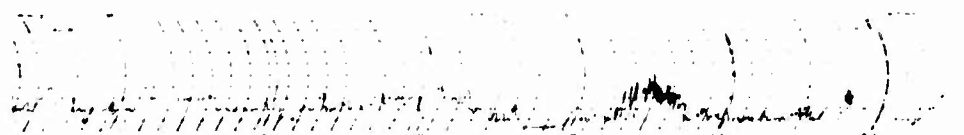

Fig. 3.21 C-W Signal at White Sands, Shot 4

Fig. 3.22 C-W Signal at Fort Sill, Shot 4

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3.5 SONIC RECORDINGS

The results of the sonic recordings are listed in Tables 3.6 and 3.7. The main purpose of these measurements was to determine the predominant period of the blast wave and to get some sort of an estimate of its amplitude at ionospheric levels. From a knowledge of the amplitude, it would be possible to estimate the velocity of the blast wave which is much greater than the normal velocity of sound (for the case of large amplitudes). Furthermore, the amplitude, expressed in terms of fractional density change (or "condensation") would be a measure of the increase in molecular density, and therefore, a measure of the corresponding change in electron density. However, the latter may not be directly proportional to the increase in molecular density, since the amplitude of the "electron wave" will depend upon many factors, including collision cross-section and probably upon the orientation of the sonic wave front with respect to the earth's magnetic field.

TABLE 3.6

Sonic Arrivals at Mather Air Force Base

Shot	Arrival	Amplitude (Microbars)	Duration (Seconds)	Remarks
4	1	9	20	
4	2	44	40	
4	3	17	10	
5	1	6	25	
5	2	52	45	
6	1	43	30	
6	2	74	65	
7	1	-	-	Doubtful - equipment erratic
7	2	79	25	
8	1	24	35	
8	2	55	30	

[redacted]

[redacted]

TABLE 3.7

Sonic Arrivals at Navajo Ordnance Depot

Shot	Arrival	Amplitude (Microbars)	Duration (Seconds)	Remarks
1	1	32	15	
1	2	47	22	
2	1	17	7	
2	2	40	17	
2	3	21	34	
3	1	53	35	
3	2	53	50	
4	1	2	10	High-frequency arrival
4	2	43	30	
4	3	38	30	
4	4	19	10	
4	5	27	10	Audible
5	1	7	30	
5	2	20	65	
5	3	15	25	
6	1	2	55	
6	2	17	150	Overlapping arrivals; audible
7	1	25	320	Overlapping arrivals; 7 audible arrivals
8	1	—	180	Overlapping arrivals

It has been shown by Schrödinger [10] that the amplitude of a plane sound wave traveling into the upper atmosphere increases, and that, if it were not for absorption, the amplitude would be inversely proportional to the square root of the atmospheric density. The absorption (which is due to viscosity and heat conduction) does not become appreciable until the wave reaches an altitude at which the mean free path of the gas molecules approaches the wave length of the sound.

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Fig. 3.23, which is based upon Schröcinger's data, shows the change in amplitude of a plane sound wave as it travels vertically into the upper atmosphere. The atmosphere is assumed to be isothermal and to have a "scale height" of 8 km (i.e., the density decreased by a factor of 1/e for each 8 km of altitude). The figure gives results for waves having periods of 5 and 10 seconds and expresses the ratio of the condensation, s, at a given altitude to that at the earth's surface, s_o, as a function of altitude. It is obvious that at frequencies as low as those assumed, the amplitude of the wave increases greatly before the effects of absorption set in. The results apply to a plane wave only, but should give a good approximation to the value for a spherical wave when multiplied by the inverse distance factor.

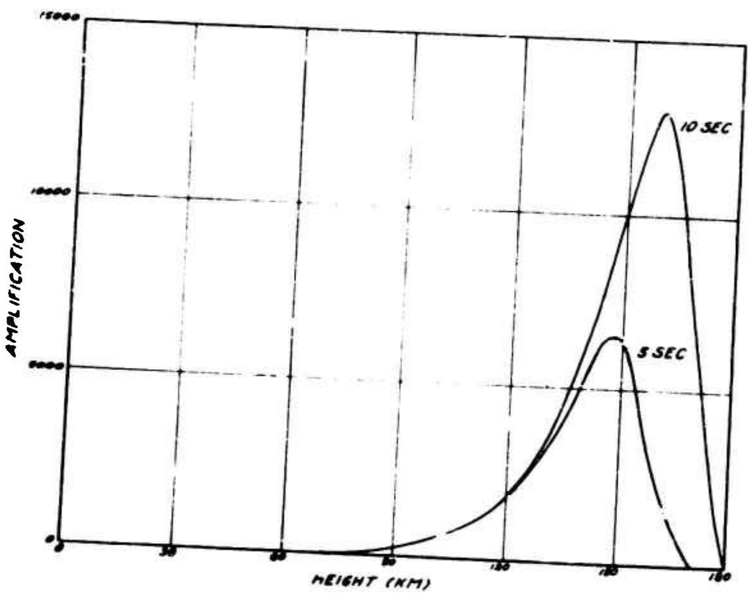

Fig. 3.23 Amplitude of a Vertically Traveling Plane Wave as a Function of Altitude

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When the value of the condensation becomes appreciably greater than unity, the velocity of the sound wave is increased, the value being given by:

$$v = v_o (1 + s)^{(\delta + 1)/2} \tag{3.1}$$

where v_o is the normal velocity, s is the condensation and δ is the ratio of specific heats.

Let us apply these results to the sound wave recorded on Shot 3. This wave, which is shown in Fig. 3.24, consisted of two separate arrivals.

Fig. 3.24 Sonic Arrivals at Navajo, Shot 3

Fig. 3.25 and Fig. 3 26 give the results of a harmonic analysis of the two arrivals. The spectrum of the first arrival has a broad peak centered near 10 seconds, whereas that of the second arrival has no such peak. Now, it is generally known that sound waves from a source at the earth's surface may be refracted back towards the earth at two levels, one near 50 km and the other near 100 km. Figure 3.27 shows the ray paths for these two types of rays, based upon an assumed atmospheric structure (the NACA Standard Atmosphere). A comparison of the two curves of Fig. 3.23 shows that the higher frequency components are more readily absorbed than the lower ones. We would, therefore, expect the frequency spectrum of a sound wave refracted at 100 km to have proportionately more low frequencies present than one refracted at 50 km. In the light of these facts, the two spectra shown permit identification of the first arrival as one refracted near the 100 km level, and the second arrival as one refracted at 50 km altitude and traveling by two hops.

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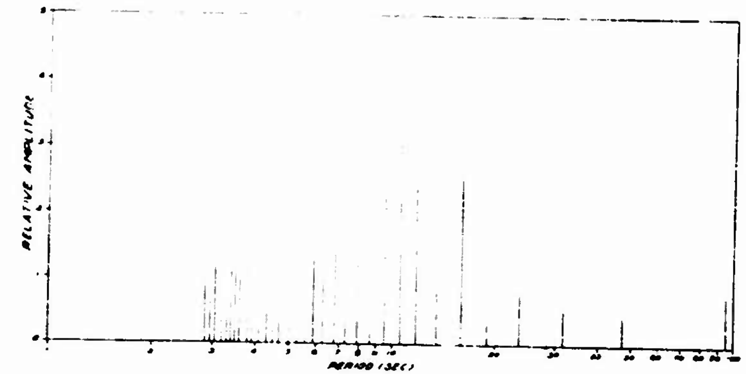

Fig. 3.25 Frequency Spectrum of First Sonic Arrival at Navajo, Shot 3

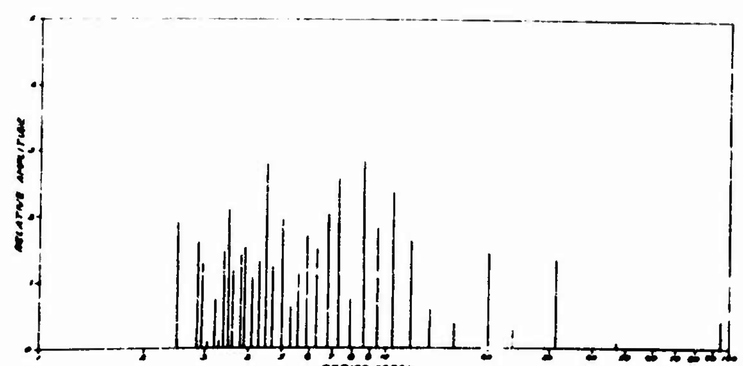

Fig. 3.26 Frequency Spectrum of Second Sonic Arrival at Navajo, Shot 3

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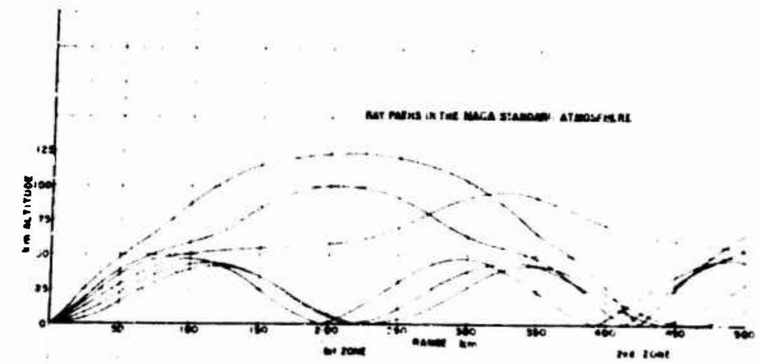

Fig. 3.27 Sonic Ray Paths in the NACA Standard Atmosphere

Starting with the recorded amplitude of the first of the two sound arrivals, use can be made of the Schrödinger theory and the velocity equation given above to get a rough estimate of the condensation and velocity at various levels. This, admittedly, will be a rough estimate, because no allowance has been made for energy lost by scattering or partial reflections at atmospheric inversions; on the other hand, no allowance has been made for focussing effects which concentrate the rays into zones, nor for the effect of winds which might strengthen or weaken the focussing effect. The approximate calculation outlined indicates that the condensation would have a value of 0.34 directly over the blast at E-layer level (110 km); this value of condensation corresponds to a velocity which is 1.4 times the normal velocity of sound. However, since most of the mathematical relations of acoustics, including the increase of condensation with altitude shown in Fig. 3.23, are derived on the assumption of exceedingly small values of condensation, it is obvious that they would not hold for a value of s as large as 0.34. As soon as the value of s becomes more than a few per cent, the wave becomes a shock wave, and subject to different laws of absorption, velocity, etc. Therefore, it is quite possible that the relation between absorption and altitude differs considerably from the one which we have used, and that the peak of the s/s_0 curve may occur at much higher levels. In fact, our observations (Table 3.5) show an effect due to the shock wave as high as 385 km, indicating an appreciable

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intensity at that level. Probably the best estimate of the intensity of the blast wave at ionospheric levels would be obtained by using the velocity equation 3.1 to calculate the condensation, starting with the observed values of velocity obtained from the ionospheric records. Of course, actual reflection heights would have to be computed and used instead of the virtual heights which are recorded by the C-3 equipment. Time has not permitted the completion of such a calculation for inclusion in the present report. A necessary result of the increase in velocity of a sound wave with increasing condensation would be a dispersion of the sound wave, because the much more intense front of the wave would travel with a higher velocity than the weaker "tail." That such dispersion does occur was pointed out above in the description of the vertical incidence soundings.

One question which is raised by consideration of the blast wave is that of the final disposition of the energy. Acoustical energy which is absorbed must reappear as thermal energy. The sudden heating of a large volume of the atmosphere would set up new oscillations, the period of which would depend upon the volume which is heated. The theory of such oscillations has been worked out for the special case of a sphere by Weber 12/, and although the theory for a sphere does not apply to the case in hand, the general conclusion can be drawn that these oscillations would be of quite long period - several minutes, at least. Furthermore, as these oscillations have their source in the upper atmosphere, much of the energy of the oscillations might be trapped in the upper one of the two ducts formed by the peak at 60 km in the velocity versus height curve; these oscillations would, therefore, not be observable at the earth's surface or would at least be greatly attenuated. Some effect on the shape of the ionospheric traces obtained with the C-3 recorder might be expected as a result of these oscillations, but in order to know what to look for, a more detailed theoretical investigation would have to be made of the magnitude and period of the oscillations.

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CHAPTER 4

DISCUSSION

4.1 EFFECT ON THE IONOSPHERE

In the above description of the results of the various types of experiments performed, an attempt has been made to explain the observed phenomena in terms of one basic physical mechanism, namely the increase of ion density caused by the blast wave as it passes through the existing ionospheric layers. Although the explanation has been mainly qualitative and many questions remain unanswered, it is felt that the basic picture of the mechanism which has been presented is essentially correct. However, because of the wealth of data obtained, considerable additional study is advisable in order to arrive at quantitative relationships between experiment and theory.

Another possible result of the blast wave on the ionosphere has been discussed in Paragraph 3.5, namely, the heating due to the passage of the blast wave, and the oscillations which might be expected as a result of this heating. A more detailed study of the data, including that taken at GREENHOUSE and BUSTER-JANGLE might give evidence as to the existence of these oscillations. Their existence might also be detected by studying sonic observations made by other groups, particularly data taken during the GREENHOUSE test.

4.2 INTERFERENCE TO RADIO COMMUNICATIONS

The degree to which radio communications would experience interruption because of the blast can best be inferred from the results of the pulse tests. According to H. O. Peterson 7/ experience has shown that when a telegraph signal is propagated via two or more paths, the circuit tends to fail when the maximum difference in arrival times exceeds half of one signal element. The unit of signaling speed commonly used is the Baud, which corresponds to one code element per second. Therefore, when the difference in seconds exceeds half of the reciprocal of the number of Bauds, the circuit will no longer be operative. On Shot 3 where the maximum time difference introduced by reflections from the blast wave was 2.5 milliseconds, failure would have been expected to occur for transmission speeds approaching 200 Bauds. Most telegraph services, with the exception of four-channel multiplex, correspond to less than 200 Bauds at all speeds up to 120 words per minute. It is thus obvious that telegraph services (exclusive of the exception mentioned) will experience little interference from a bomb the size of Shot 3. In any case, the interference would last only for a few minutes.

Interference to speech transmission would, of course, be more severe. Work done at Signal Corps Engineering Laboratories by A. Ross 9/ with a multipath simulator indicates that 3 milliseconds delay

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would reduce the intelligibility of speech to 33 per cent for amplitude modulation and 10 per cent for frequency modulation. However, as mentioned above in connection with telegraph interference, the effect would last only for a few minutes for a weapon the size of the one used in Shot 3. Of course, the above conclusions apply only to the particular path under consideration. The ray paths of transmissions originating near the blast site and received at quite remote locations would pass through the ionosphere at points which are located some distance laterally from ground zero, and would not be expected to suffer so much interference as a ray which is refracted directly above the blast.

Another possible mechanism of interference which was mentioned in connection with the discussion of GREENHOUSE, is that radio waves may be absorbed by the atomic cloud which remains for some time after the blast. No experiments have yet been made which were designed specifically to check this phenomenon. As this is purely an absorption phenomenon, and, therefore, more pronounced at the lower frequencies, adverse effects on communication could be partially overcome by using the higher frequencies in the HF band or by using VHF whenever practical. In any case, absorption by the atomic cloud would affect only ionospheric communications to or from localities in the immediate vicinity of the blast site, and would not affect ionospheric circuits, the terminals of which are at some distance from the site.

4.3 APPLICATION TO LONG-RANGE DETECTION

The fact that C-8 transmissions to points 1300 miles distant were noticeably affected by the blast raises the question as to the possibility of detecting an atomic explosion at great distances by means of radio observations. In this connection, it should be pointed out that the transmitter was relatively near the blast site (311 miles) and that radio transmission to the receiver site occurred by relatively few modes. This combination would probably be optimum for production and detection of beats between the normal modes and the rays reflected from the blast wave. (When transmission occurs by many modes, interference between them results in fading which closely resembles that due to the blast.) Furthermore, the long-range effect was noticed only at those times of the day when an E layer was present (i.e., during the daylight hours). These considerations lead to the conclusion that detection might be accomplished if an enemy station operating on an appropriate frequency and located near the blast site could be monitored by a receiver located on the opposite side of the blast. Such a scheme probably would work only during the hours when an E layer is present over the atomic test site.

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4.4 VALUE OF ATOMIC EXPLOSIONS AS A TOOL IN IONOSPHERIC RESEARCH

The detailed description of the results gives some indication of the value of atomic explosions as a tool in ionospheric research, as well as possible lines along which such work could be directed. For the first time, we have a method of causing a transient pressure change in the upper atmosphere, and by means of vertical or oblique incidence radio signals, some of the effects of this pressure change may be observed. The exact amount of the pressure increase is not known, but probably could be best calculated from the radio observations themselves (i.e., from the apparent velocity of the blast wave). Furthermore, with a better understanding of the relationships existing between the various parameters, it might be possible to obtain more accurate information regarding the temperature of the upper atmosphere than is presently available.

One of the direct effects of the blast wave was found to be a phenomenon very similar to one of the types of sporadic-E reflections which appear on ionospheric sounding records, and this observation may lead to an explanation of the nature of sporadic E. The proposal has been made by many workers in the field that sporadic E may be a scatter phenomenon, and H. G. Booker 1/ has recently developed an expression for the amount of scattering as a function of the critical frequency of the layer, the dimensions of the scattering "blobs", and the fractional increase in density of the blobs with respect to their surroundings. According to Booker's result, the scattered energy is proportional to the square of the average ion density. The approximate calculation made in paragraph 3.5 indicated that the blast wave of Shot 3 increased the ion density by a factor of about 1.34, the square of which is 1.8. Thus the energy returned in the direction of the transmitter by any blobs which happened to be present would have been approximately doubled by the action of the blast wave, and if this doubling were sufficient to increase the level of a previously undetectable signal to a point above the threshold of the equipment, it would have been visible on the oscilloscope screen. (Actually the density increase in the case of Shot 3 may have been much greater; computations based upon the yield, instead of upon the sonic data, indicate that this is the case.) The above considerations suggest that the formation and decay of sporadic E may be due to atmospheric oscillations. Any type of atmospheric oscillation would have a much greater amplitude at ionospheric levels than at the earth's surface, and the corresponding density changes may be sufficient to cause the scattered return to fade in and out on the oscilloscope of the ionosphere recorder.

The observation that sound waves can refract or scatter radio waves introduces many other new possibilities. The suggestion has

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already been made by one of the authors of the present report 5/ that sound waves which are generated by the piston action of the ocean waves may be the cause of the apparent twinkling of radio stars, although the density changes involved would be much too small to account for sporadic-E reflections. (According to Booker's formula, the scattered energy is much less in the backward direction than for forward scattering.) It should be possible to check this hypothesis experimentally with atomic explosions or even with much smaller TNT detonations.

It must be admitted that the use of atomic blasts also has its disadvantages. The radio spectrum is so cluttered up with interference immediately after a blast, apparently from radio-controlled equipment used in connection with the test, that the ionospheric reflections are often almost completely obscured. A solution to this problem would be an atomic test planned specifically for research purposes and unaccompanied by radio interference. Another solution would be a more carefully planned choice of the interfering frequencies, so that interference at those frequencies of greatest interest would be eliminated.

CHAPTER 5

CONCLUSIONS

5.1 EFFECT ON THE IONOSPHERE

All of the propagation effects observed during the TUMBLER-SNAPPER shots can be attributed to the local increase in ion density caused by the blast wave as it passed through the ionospheric layers.

5.2 INTERFERENCE TO RADIO COMMUNICATIONS

Interference to radio communications caused directly by the blast wave lasted only a few minutes, and was primarily due to the occurrence of additional modes of propagation caused by reflection of the radio waves from the blast wave. During the time that such interference was present, speech transmission probably would have been impossible, but code transmission would not have been seriously impaired. No interference due to secondary effects, such as absorption by the atomic cloud was observed during the TUMBLER-SNAPPER shots. Of course, these conclusions apply only to weapons of the size used in the TUMBLER-SNAPPER shots. The results of propagation tests performed at Operation IVY should indicate whether larger weapons cause correspondingly greater interference, or possibly interference of a different nature.

5.3 LONG-RANGE DETECTION

Under certain limitations, interference caused by the blast might be used for long-range detection of atomic explosions; this could be accomplished by monitoring a suitably located enemy transmitter.

5.4 ATOMIC EXPLOSIONS AS A RESEARCH TOOL

Atomic explosions provide a tool which should be of great value in ionospheric research, but its usefulness is somewhat limited by radio interference which is presumably caused by associated control and telemetering equipment.

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CHAPTER 6

RECOMMENDATIONS

6.1 ADDITIONAL STUDY OF DATA

It is recommended that study of the data obtained on TUMBLER-SNAPPER and previous tests be continued in order to attempt to establish quantitative relationships between the phenomena observed and parameters of the disturbed and normal ionosphere.

6.2 CLASSIFICATION

It is further recommended that the vertical incidence data be given as low a security classification as practicable. This would permit maximum dissemination of the results and thus encourage discussion and additional work in a field which is believed to be of great value from the standpoint of atmospheric physics.

6.3 LARGER WEAPONS

The effects of weapons larger than those used in Operation TUMBLER-SNAPPER should be investigated. (Such tests were carried out at Operation IVY.)

6.4 LONG-RANGE DETECTION

The possibility of Long-Range Detection should be tested on larger weapons. (This work was also included in Operation IVY.)

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